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Fault Tree Analysis of Bradley Linebacker

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Fault Tree Analysis of Bradley Linebacker

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Abstract

This report presents a version of the degraded states (DS) methodology, concentrating on the logic used within fault trees. This methodology was the basis for the system analysis conducted on the Bradley Linebacker. This methodology and analysis were documented within the System Analysis Report (SAR) of J. F. Meyers, B. G. Ruth, and R. W. Kunkel entitled, "Survivability/Lethality Analysis Report for the Bradley Linebacker," from the U.S. Army Research Laboratory, Aberdeen Proving Ground, MD in October 1996, in support of the U.S. Army Operational Evaluation Command (OEC) in the preparation of the System Evaluation Report (SER). The Bradley Linebacker is an enhancement to the Bradley Fighting Vehicle (M2A2) with the ability to select targets, automatically track targets, and launch Stinger missiles. This is the first integrated system performed on any system where synergy of different battlefield threats was considered.

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1. Introduction

1.1 Background. The Degraded States Vulnerability Methodology (DSVM) is an analytical process for the determination of (either residual or lost) capability of a combat system following an encounter with a damage mechanism (Abell, Roach, and Starks 1989). The DSVM was developed in 1988 by the Ballistic Vulnerability Lethality Division (BVLD) (now the Ballistics NBC Division [BND]) in conjunction with the vulnerability/lethality (V/L) process structure, as shown in Figure 1. The V/L process structure was later modified by Ruth and Hanes (1996) to include the concept of time (shown in Figure 2). The degraded states (DS) is the methodology derived from using the process structure to carry out a V/L analysis on a system.

1.2 Objective. This report presents a version of the degraded states (DS) methodology, concentrating on the logic used within the fault trees. This methodology was the basis for the system analysis conducted on the Bradley Linebacker. This methodology and analysis were documented within the System Analysis Report (SAR) (Myers, Ruth, and Kunkel 1996), in support of the U.S. Army Operational Evaluation Command (OEC) in the preparation of the System Evaluation Report (SER). The Bradley Linebacker is an enhancement to the Bradley Fighting Vehicle (M2A2) with the ability to select targets, automatically track targets, and launch Stinger missiles. This is the first integrated system performed on any system where synergy of different battlefield threats was considered.

2. Approach/Methodology

Within BND, the first step in implementing the DSVM lies in the precise description of level-3 system-level capabilities within three simple categories: ability to move, ability to operate, and ability to communicate, which could also be capability categories. In this particular Bradley Linebacker analysis, the aforementioned categories were used as a guide. The approach for this case was to map the categories into tasks identified in Martin (1996). The results were as follows.

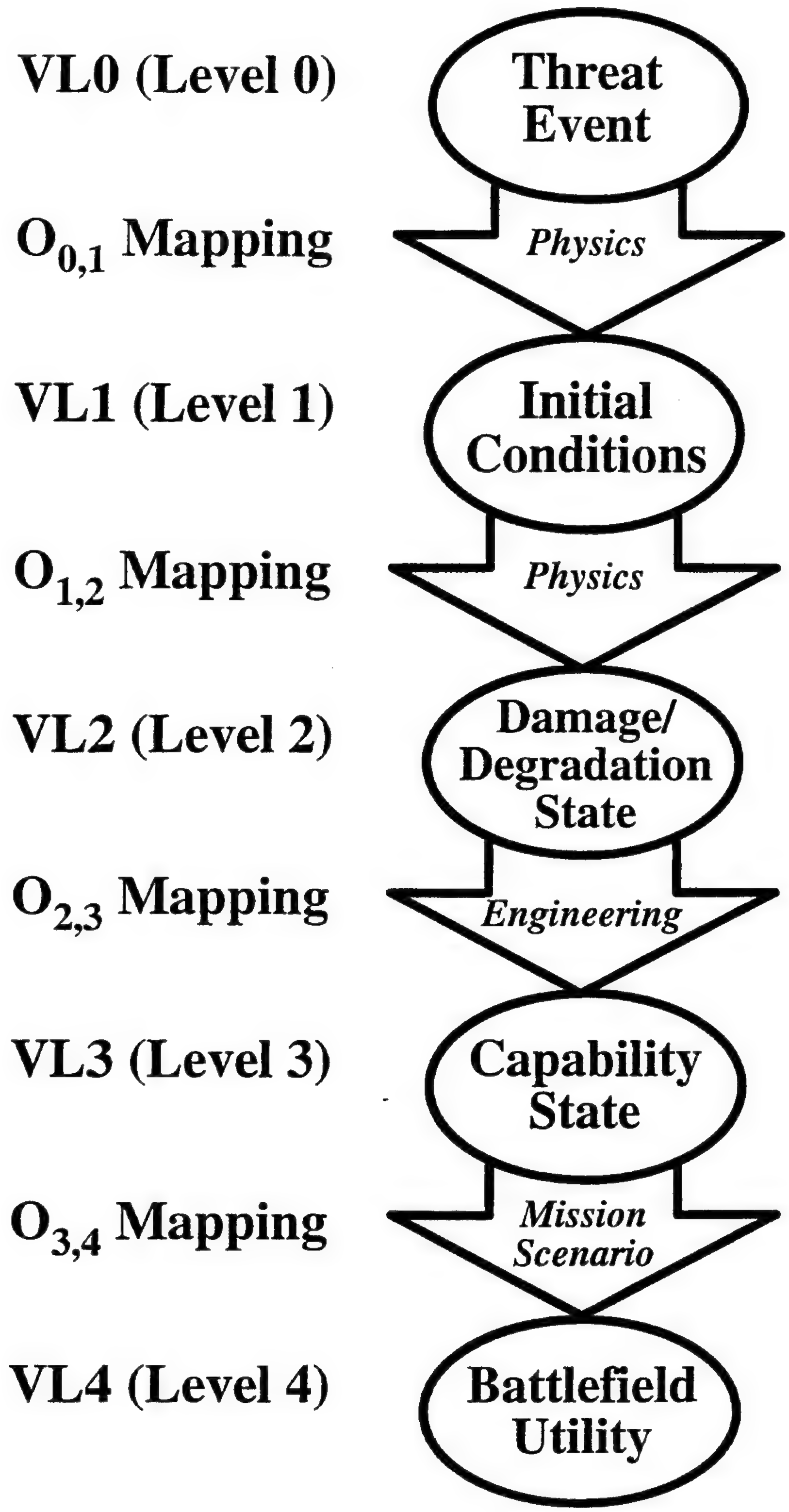

Figure 1. The VL Taxonomy.

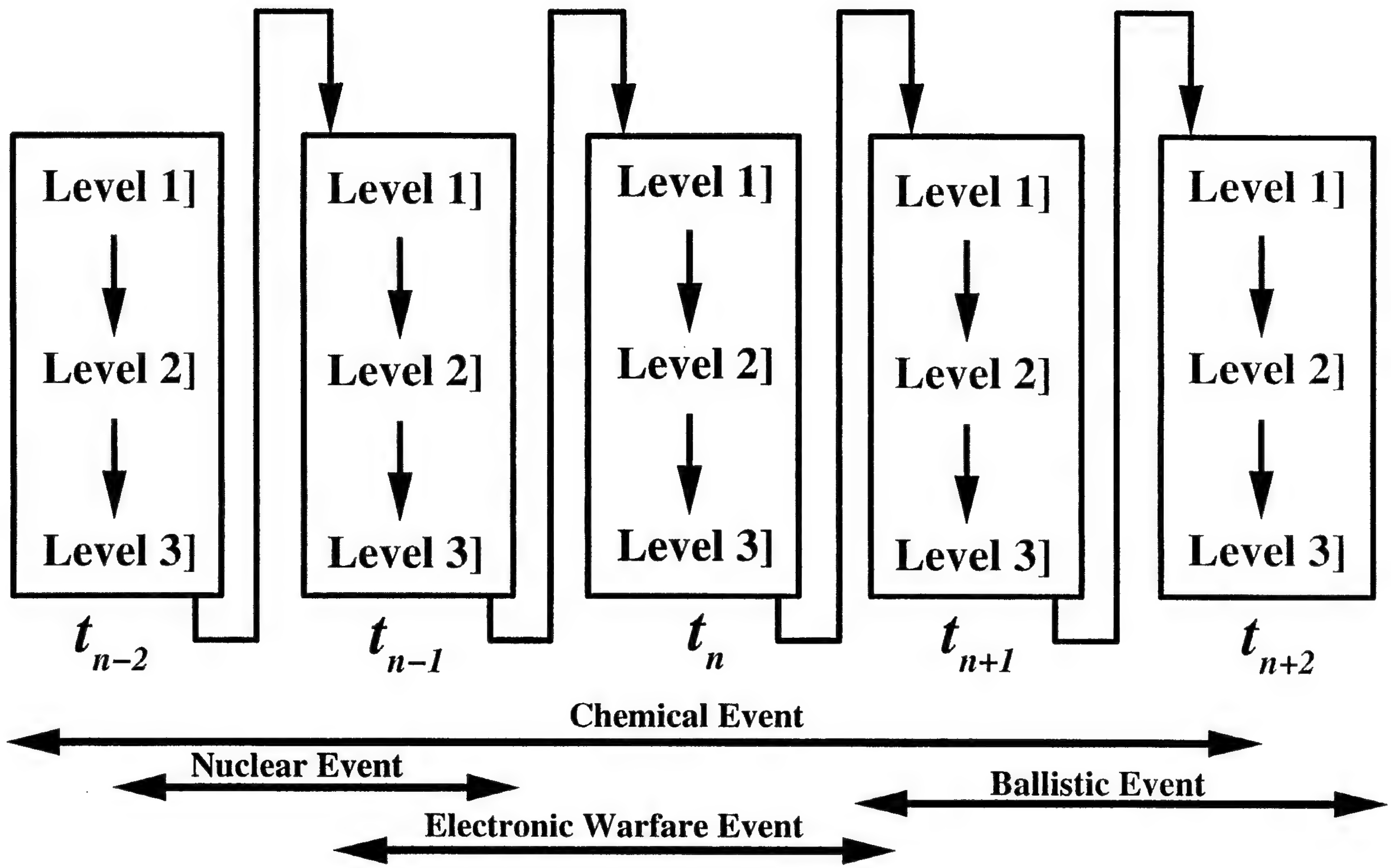

Figure 2. The Time-Discrete Vulnerability/Lethality Process Structure.

- Ability to move ————> ability to move (mobility) (M).

- Ability to operate ————> ability to operate weapons (OW),
  ————> ability to operate Stinger (OS).

- Ability to communicate.

This was a slight variation from the standard approach. As one will notice, the ability to communicate is not mapped to any Bradley Linebacker task. In this particular case, the ability to communicate is defined as internal verbal exchange between crew members or external verbal exchange between crew members and others within the Bradley Linebacker's military chain of command. No task(s) appeared within the Bradley Linebacker's operational mode summary/mission profile (OMS/MP); therefore, the ability to communicate was not mapped into any of the Bradley Linebacker's tasks. With the three new categories being considered, and as applied to the Bradley Linebacker capabilities analyzed in this report, each capability is equivalent to the task identified in the Bradley Linebacker mission profiles. Eight capabilities of interest have been addressed within either M, OW, or OS categories, as follows.

- M

  - M1: Ability to move the Bradley Linebacker (M2 CARRIER/MOVE TASK).

- OW

  - OW1: Ability to search for a target (WEAPONS/SEARCH TASK).

  - OW2: Ability to acquire a target (WEAPONS/ACQUIRE TASK).

  - OW3: Ability to identify friend or foe (WEAPONS/IDENTIFY TASK).

- OW4: Ability to track a target (WEAPONS/TRACK TASK).

• OS

- OS1: Ability to engage a target (Stinger/ENGAGE TASK).

- OS2: Ability to reload/rearm the Stinger missiles (Stinger/RELOAD REARM TASK).

- OS3: Ability to hit a target (not considered within the OMS/MP).

The aforementioned capabilities M1, OW1 through OW4, and OS1 through OS3 are listed in order of precedence, as outlined in the operational mode summary/mission profile (OMS/MP). In other words, there is a specific sequence that must be followed in order to successfully implement these capabilities within a mission profile. First, the platform must be able to move (M1) in order to arrive at its destination. It also has to be able to fire on the run. Secondly, target information is passed from an information gathering source to the Bradley Linebacker. This allows a crew member to search in the general direction for a potential target (OW1) based on that information. Next, the Linebacker must acquire the target (OW2). After acquisition, the Linebacker must identify the target as friend or foe (OW3). Then, the Linebacker must be able to track the target as it moves (OW4). Following OW4, the Linebacker must be able to engage the target (OS1). Finally, the crew within the Linebacker must be able to rearm/reload the Stinger missiles (OS2). All of these activities have the potential to occur while the Bradley Linebacker is mobile (M). The last of the operate Stinger capabilities (OS3) is not listed in the Linebacker operational requirements document (ORD) as a Linebacker capability, although it is considered within the scope of this integrated V/L analysis. The reason for this is two fold: the first being that the Linebacker was designed with the intention that it would deliver the Stinger missile. The Stinger missile is a fire-and-forget missile, meaning it will not receive any further instructions from the Linebacker once it is launched. The second is to see if the Stinger missile is susceptible to the electronic warfare (EW) threat within this analysis.

The second step in the DSVM involves the construction of a fault tree for each system-level capability. As utilized within the $O_{2,3}$ mapping, a fault tree is a methodology to logically connect all of the components within a system that contribute to a particular system-level operational capability. These components are represented within a fault tree by their associated component states, which can be either damage or resource flow interruption (RFI) states, depending on the threat that interacts with a target system. In general, for a specific threat, the component states within a fault tree will consist of either physical damage or RFI states (an exception to this rule involves mission-oriented protective posture [MOPP] IV compatibility with the crew member components; this exception will be explained later).

2.1 Damage States

2.1.1 Component Damage States. Within a fault tree, component damage (CD) states are interconnected in either serial or parallel paths (or combinations of the two). CD states connected in series are combined using the Boolean AND (multiplicative) operator, while CD states connected in parallel are combined using the Boolean OR (additive) operator. CD states are evaluated within the inclusive unit interval [0, 1], where a state of 1 indicates a fully functional component, and a state of 0 indicates a fully nonfunctional component. Table 1 defines the mathematical operation of the Boolean AND and OR operators. In the present analysis, all CD states are limited to the binary values 0, 1 or the approximate state [0, 1]. An approximate state is a state that is used to represent CD when the analyst has determined that some unquantifiable amount of damage has occurred, whether it be from "engineering judgment" or some type of measurable data.* To obtain the capability metric associated with a fault tree, the entire tree is evaluated (the calculation of a logical Boolean product) by tracing a continuous path from the top (represented by a box with a single asterisk) to the bottom (represented by a box with a double asterisk) of the tree. All components critical to the operation of a specific capability are included in a tree structure; the loss of any component connected in series would disrupt the top-to-bottom path through the tree, whereas those components listed in parallel must all be killed (State = 0) to interrupt the path.

* See the appendix for more explanation of Boolean three-value logic.

Table 1. Boolean Mathematical Operations Using Binary (0 and 1) and Approximate [0, 1] Component Damage States

AND Operator		
Value of Component No. 1	Value of Component No. 2	Net Component State = Component No. 1 AND Component No. 2
0	0	0
0	1	0
1	0	0
1	1	1
[0, 1]	0	0
0	[0, 1]	0
[0, 1]	1	[0, 1]
1	[0, 1]	[0, 1]
[0, 1]	[0, 1]	[0, 1]
OR Operator		
Value of Component No. 1	Value of Component No. 2	Net Component = Component No. 1 OR Component No. 2
0	0	0
0	1	1
1	0	1
1	1	1
[0, 1]	0	[0, 1]
0	[0, 1]	[0, 1]
[0, 1]	1	1
1	[0, 1]	1
[0, 1]	[0, 1]	[0, 1]

Figure 3 shows the fault tree for a generic target classification subsystem. In this example, critical components required to classify a target include one C-band or wide-band antenna, a receiver, a signal processor, a data processor, and a display terminal. The CD states of the three antennas, which are considered redundant, are evaluated and then linked together through the Boolean OR operator. This implies that at least one of the antennas must remain functional in order for the subsystem to classify a target (the wide-band antenna is assumed to cover the C-band frequency range). The remaining four components are in series, therefore implying each one of these components must function in order for the subsystem to classify a target. Thus, these CD states are linked together through the Boolean AND operator.

2.1.2 RFI/Corruption States. Within a fault tree, CD states are assigned to the corresponding component box. However, RFI and resource corruption (RC) states are analyzed a bit differently within a tree. An RFI state depends on the effect the threat has on the individual subsystems flow of a resource (such as electrical current, mechanical force, digital information, or the task-dependent action of a soldier) between the component in question and all other components either electrically, mechanically, or operationally connected to the first. In this case, the threat usually imposes a "back-and-forth" change in state, without causing any physical damage to the component. An example is the effect a smoke or obscurant has on a laser beam over a period of time. When the smoke or obscurant is dense, the laser beam is not able to penetrate, but as the smoke or obscurant dissipates, the laser is able to reach its intended target. Note, this threat effect may be cyclic over a given time period and thus produce the back-and-forth change of state, as mentioned earlier. Again, this takes place with no physical damage to the component producing the laser beam. Thus, a RFI state is determined by evaluating the state of the resource flowing in or out of the component. This evaluation is done at what is termed a node within the tree. The example fault tree in Figure 3 contains five node points labeled A, B, C, D, and E, where the RFI states of the antenna (whichever one is used), the receiver, the signal processor, the data processor, and the display terminal are evaluated, respectively. If any of these critical components are exposed to a battlefield threat that interrupts that component's performance (without causing any permanent damage to the component), then, within a fault tree, the state of the resource flowing out of the component into a node point is interrupted in a corresponding fashion. In order to evaluate the capability metric associated with a

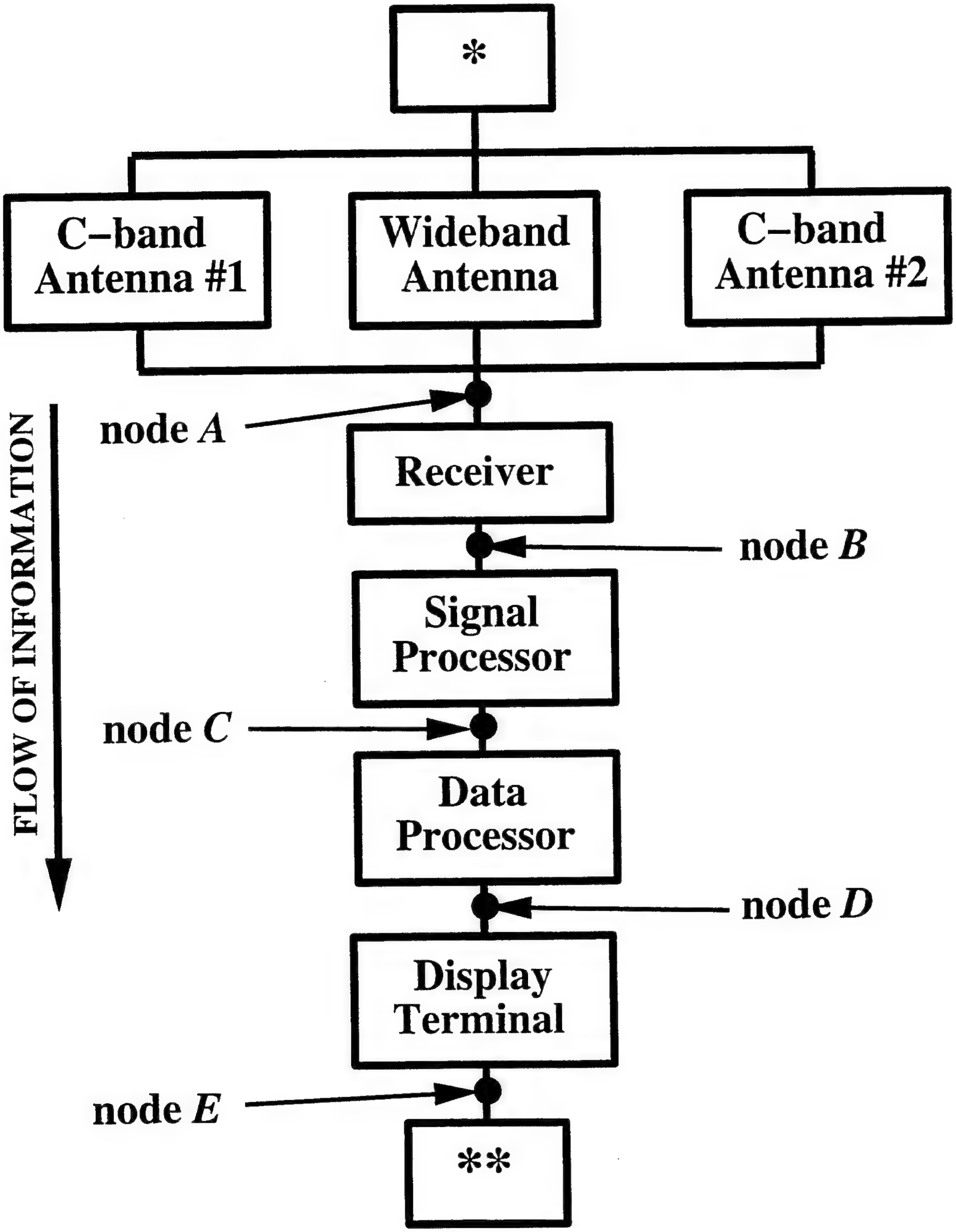

Figure 3. Fault Tree for a Generic Target Classification Subsystem.

fault tree, the RFI states within the tree are linked together using the Boolean AND operator. These RFI states are measured at specified nodes. Fractional values of a component resource are defined as x/100. Table 2 defines the mathematical operation of the Boolean AND operator as it is used to connect RFI states. Again, as seen in Table 1(a), the Boolean AND is being applied, implying that the Boolean outcome of component no. 1 will be multiplied to the Boolean outcome of component no. 2 to produce the net component state.

Table 2. Boolean AND Operation Using Binary (0 and 1) and Fractional (x/100) RFI States

Value of Component No. 1	Value of Component No. 2	Net Component State = Component No. 1 AND Component No. 2
0	0	0
0	1	0
1	0	0
1	1	1
x/100	0	0
0	x/100	0
x/100	1	x/100
1	x/100	x/100
$x_1/100$	$x_2/100$	$(x_1 x_2)/10{,}000$

Next, we use the target classification fault tree in Figure 3 to illustrate how a capability metric is affected by different threat environments. Let us suppose that a ballistic threat has killed "C-Band Antenna No. 1." Then we can calculate the capability "Ability to Classify a Target" as:

$\text{Capability}_{\text{classify}}$ = ([C-Band Antenna No. 1 = 0] OR [Wide-Band Antenna = 1] OR [C-Band Antenna No. 2 = 1]) AND (Receiver = 1) AND (System Processor = 1) AND (Data Processor = 1) AND (Display Terminal = 1) = 1.

In another scenario, suppose a chemical agent has dissolved materials within "Wide-Band Antenna" and "Display Terminal," possibly rendering these components partially operable or inoperable, so that the net CD state now becomes

$\text{Capability}_{\text{classify}}$ = ([C-Band Antenna No. 1 = 1] OR [Wide-Band Antenna = [0, 1]] OR [C-Band Antenna No. 2 = 1]) AND (Receiver = 1) AND (System Processor = 1) AND (Data Processor = 1) AND (Display Terminal = [0, 1]) = [0, 1].

An RC state relies on the true output reading of an algorithm within a component at an instant of time. Imagine a third scenario where an electronic countermeasure (ECM) has resulted in a false target, which the target classification subsystem has classified as a real target. There is no component damage in this scenario; there is, however, considerable RC to the subsystem performance due to the presence of the ECM. Now, because the ability to classify a target is produced by an aggregate synergism between all critical components in the subsystem, we really only need to evaluate the RC state (false information flowing between components) at node E (although the subsystem may have been adversely affected at any one, or more, of the components). This is the point where target classification information becomes available to the soldier. Due to the effect of the ECM,

$$\text{Capability}_{\text{classify}} = \text{information state at node E} = 0.$$

This basically tells us that the target classification system is unable to distinguish a false target from a true one. For more information regarding the aforementioned states see Ruth (1996).

2.2 Fault Trees. Figures 4–11 show the eight fault trees used in the present integrated V/L analysis of the Bradley Linebacker. Indicated at the top of each figure is the associated system-level residual capability that the fault tree is used to calculate. The "at" (@) symbol next to a box within a fault tree indicates an embedded (child) tree within the box, which is evaluated before the (parent) tree. The output from an embedded tree is then inserted into the corresponding box within the parent tree. Figures 12–14 show the embedded "child" fault trees associated with the trees shown in Figures 4–11.

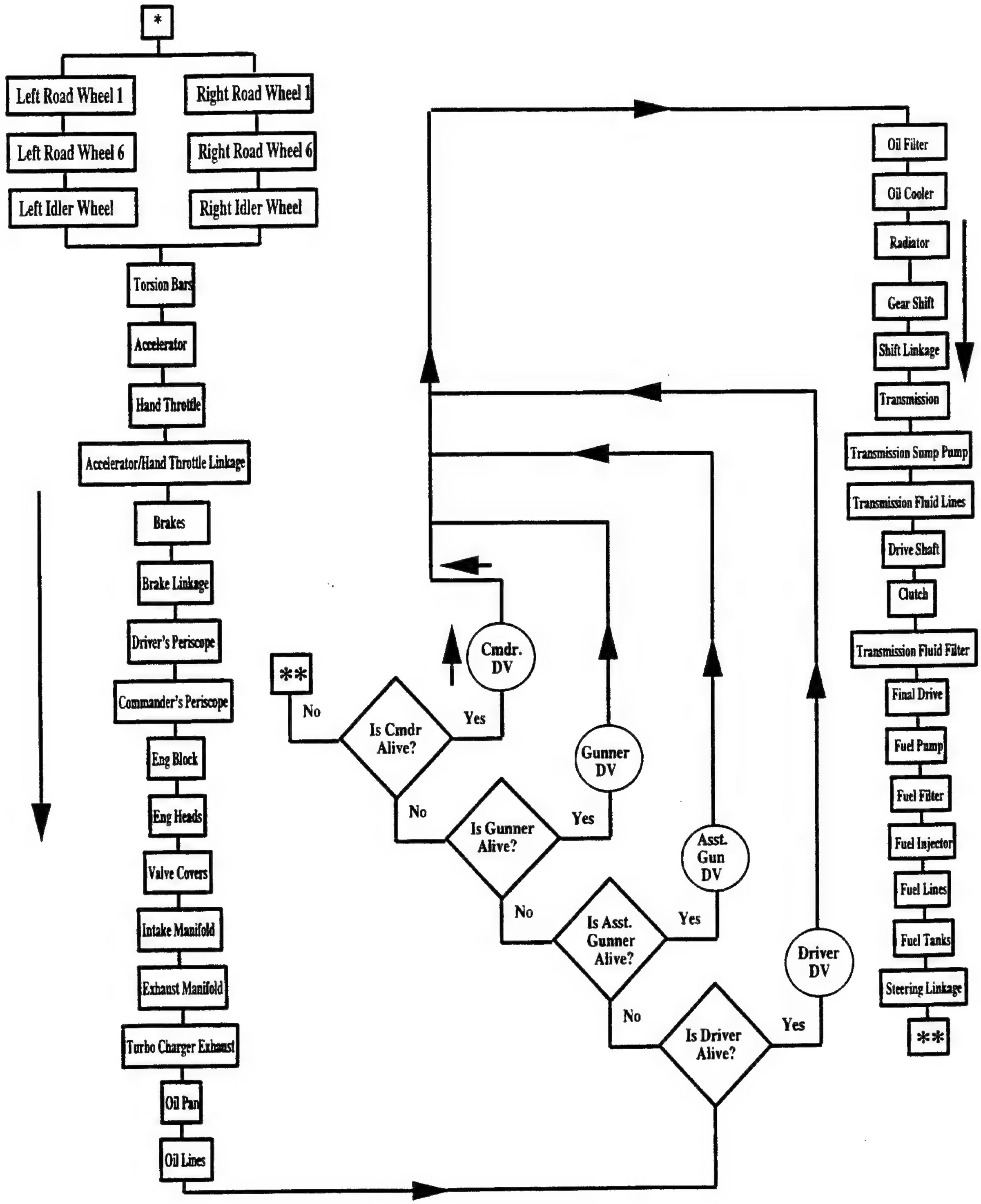

Figure 4. M1 - Ability to Move.

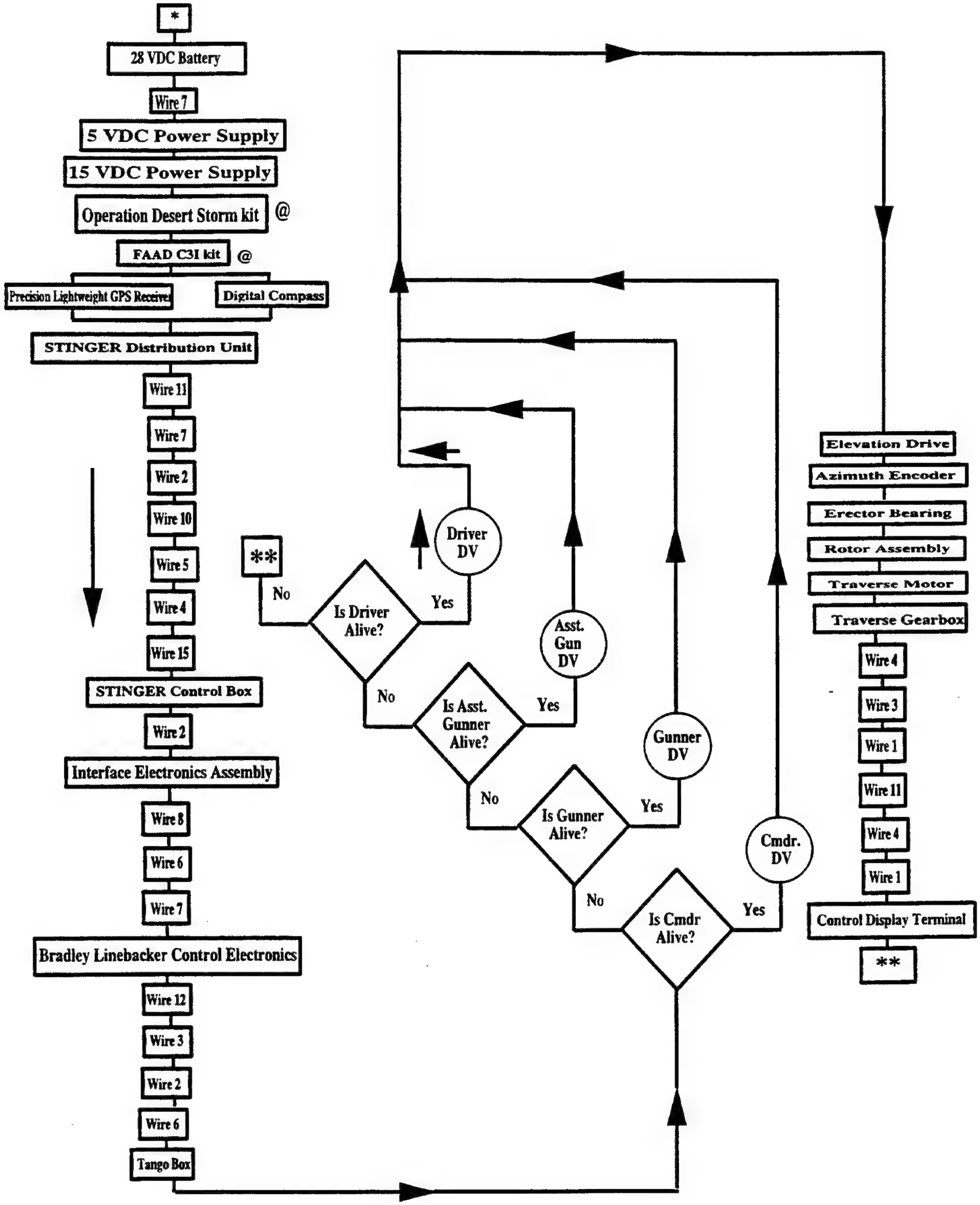

Figure 5. OW1 - Ability to Search for Target Information.

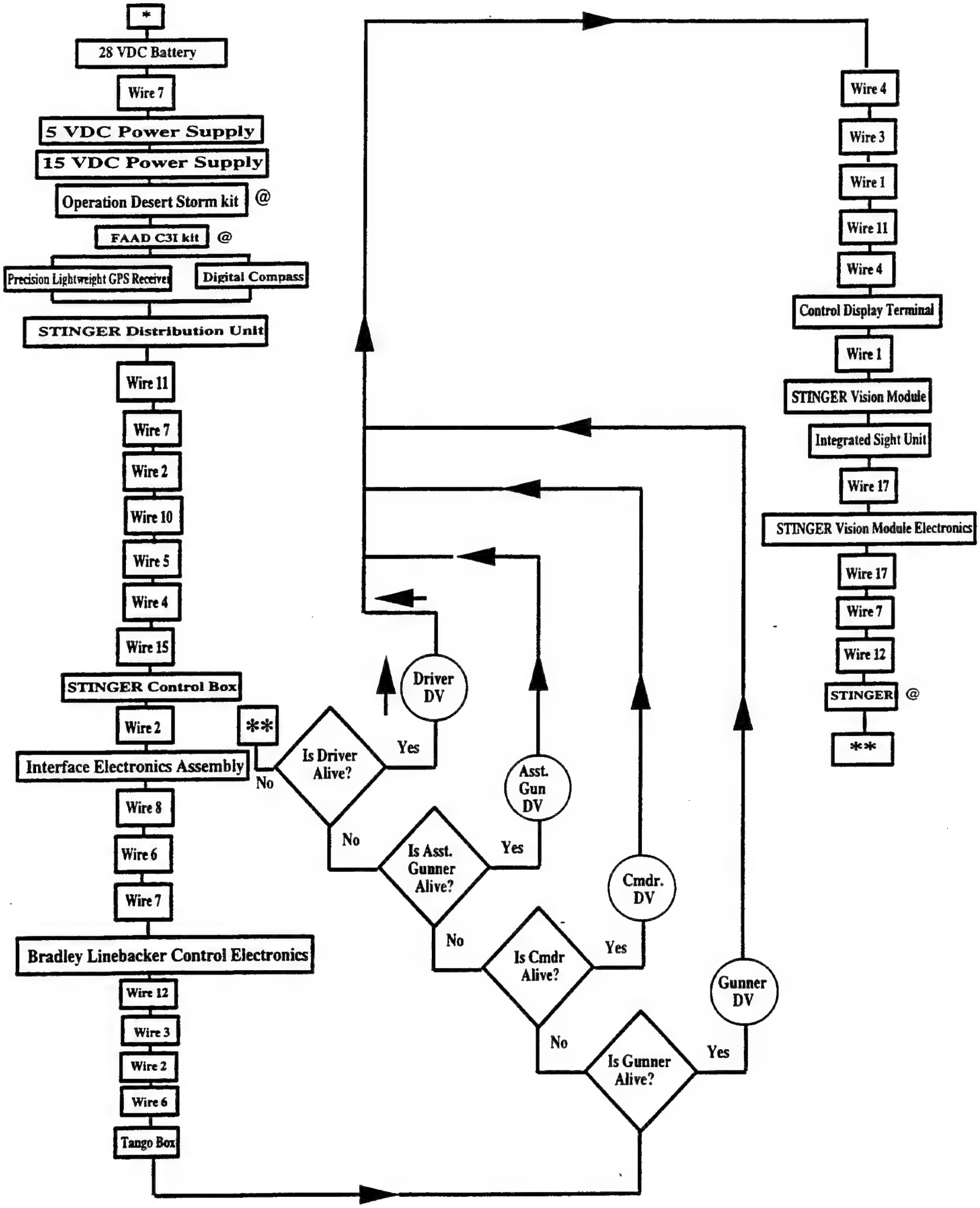

Figure 6. OW2 - Ability to Acquire a Target.

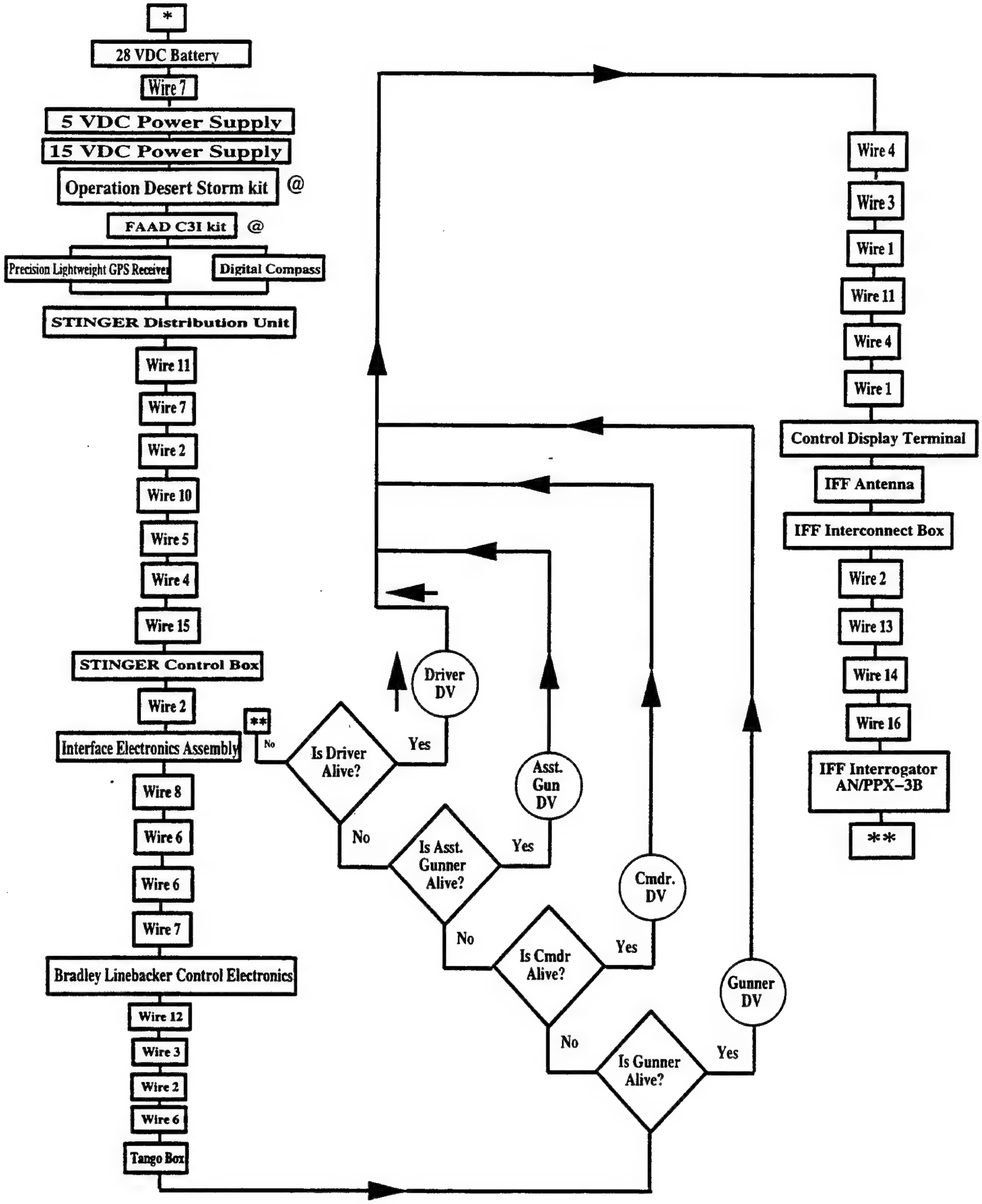

Figure 7. OW3 - Ability to Identify Friend or Foe.

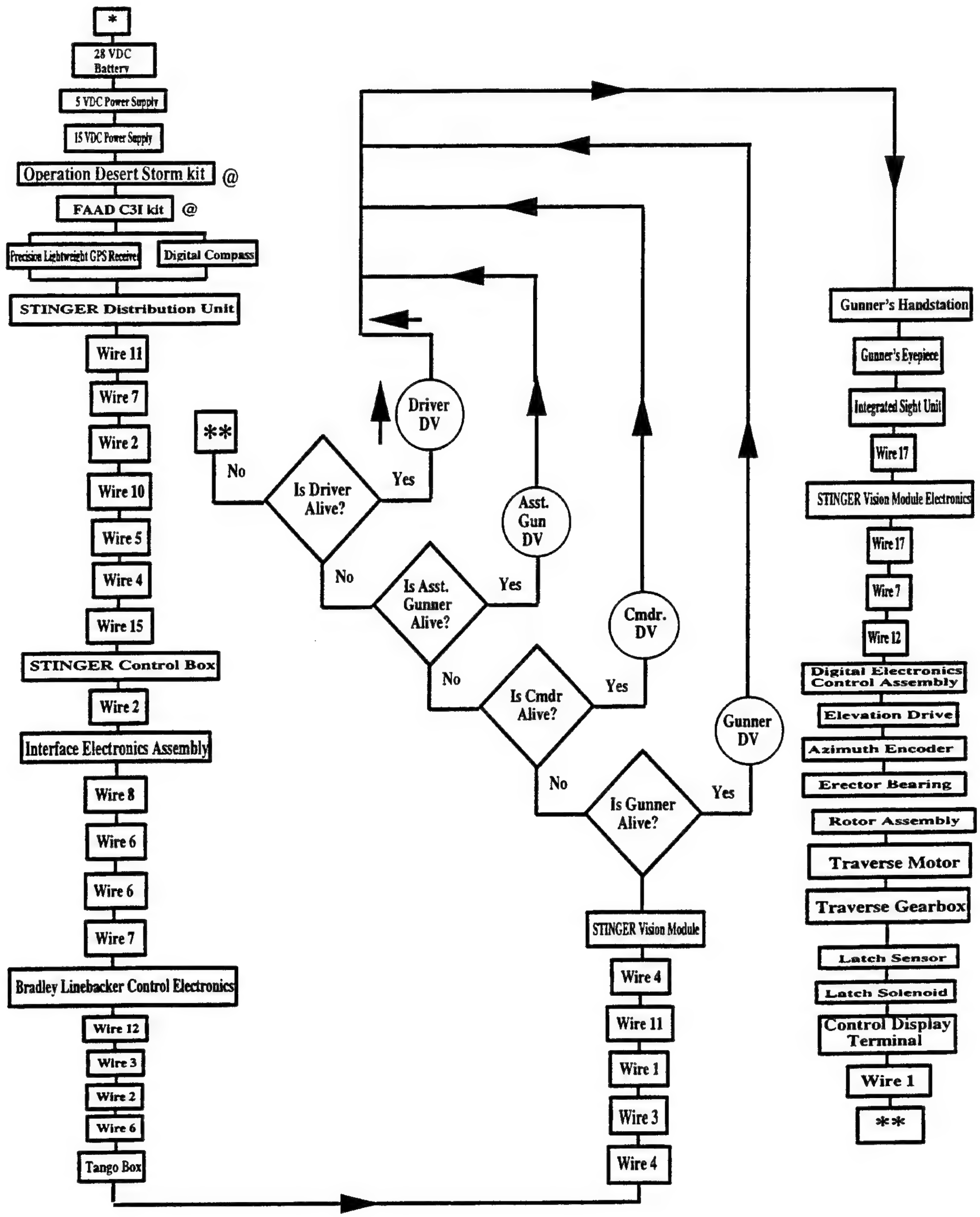

Figure 8. OW4 - Ability to Track a Target.

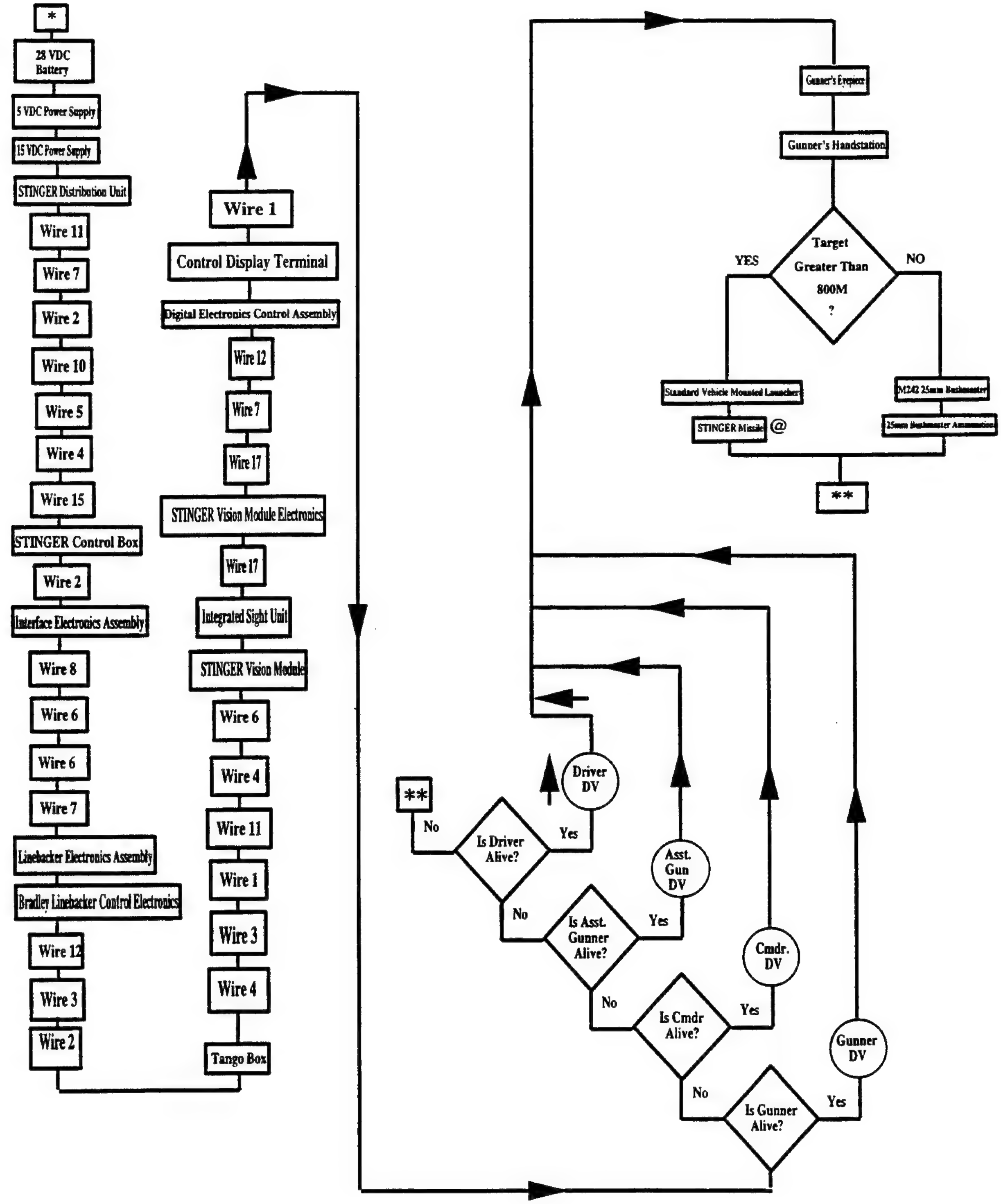

Figure 9. OS1 - Ability to Engage Target.

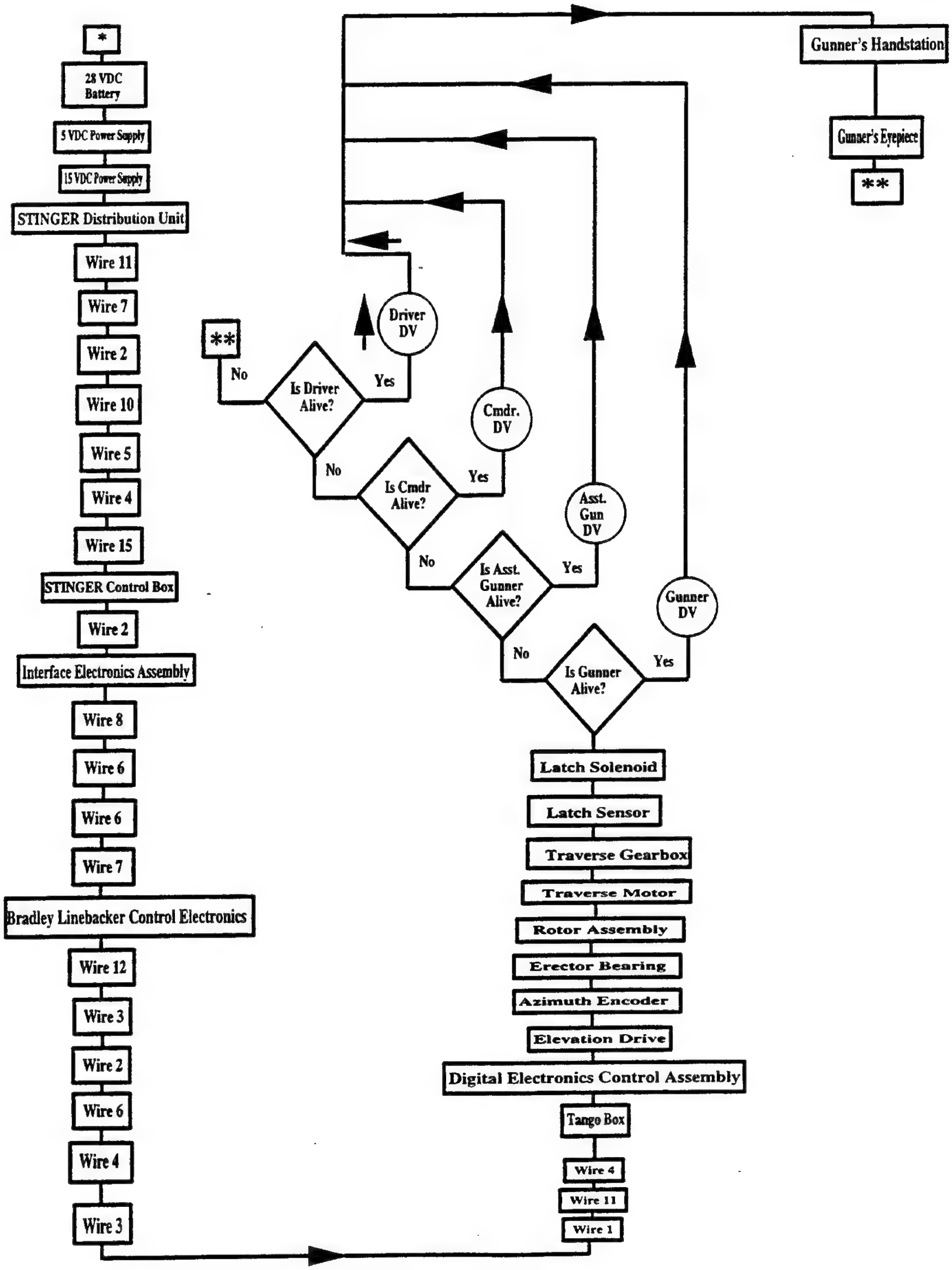

Figure 10. OS2 - Ability to Rearm/Reload Stinger Missile.

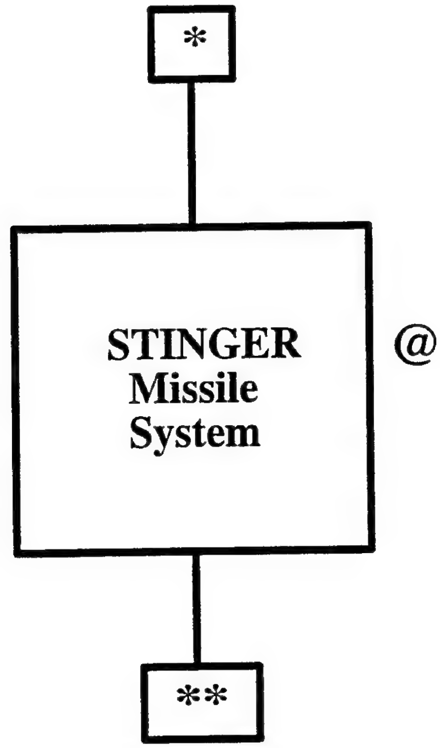

Figure 11. OS3 - Ability to Hit a Target.

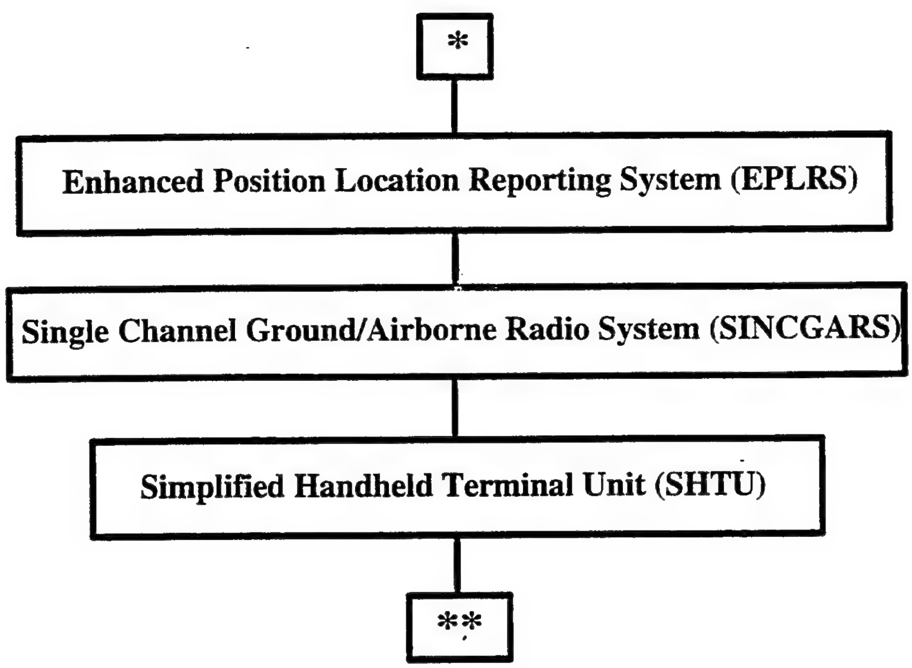

Figure 12. Embedded "Child" Tree - FAAD C31 Kit.

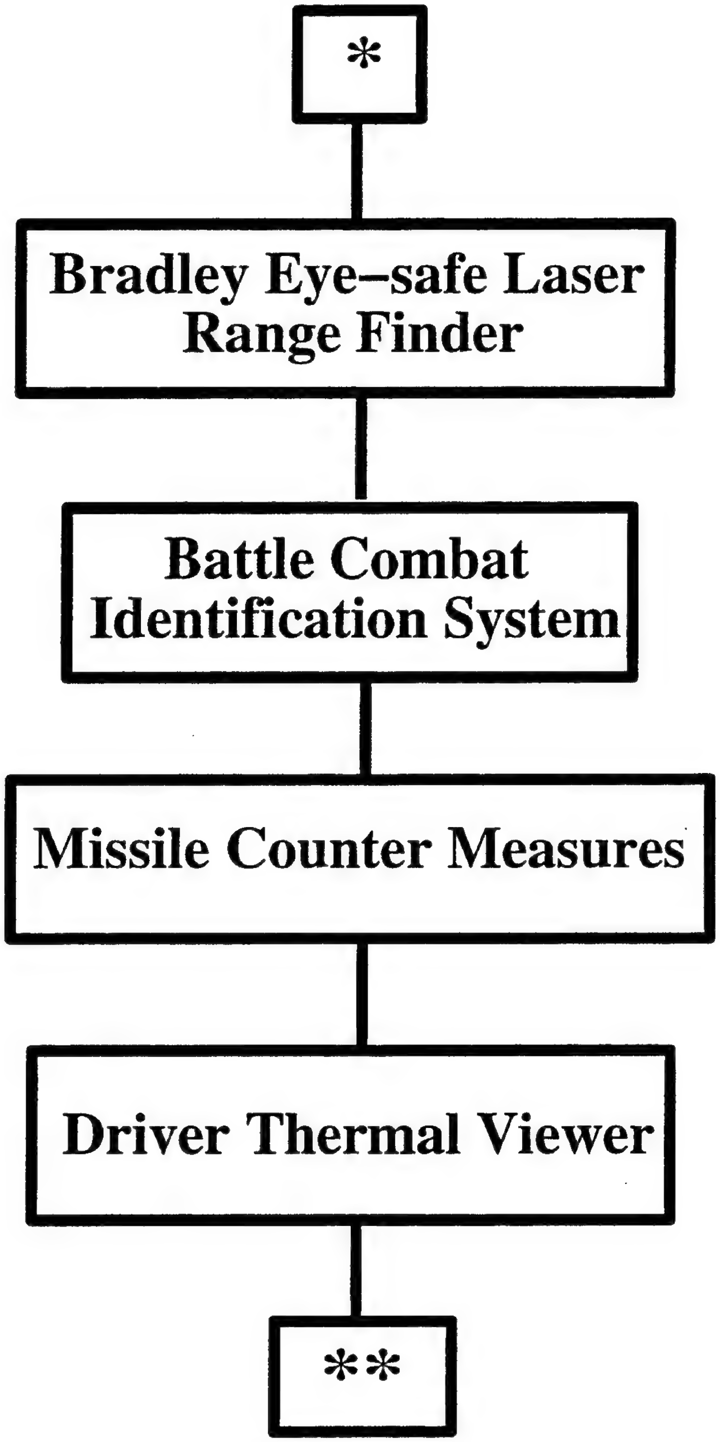

Figure 13. Embedded "Child" Tree - Operation Desert Storm Kit.

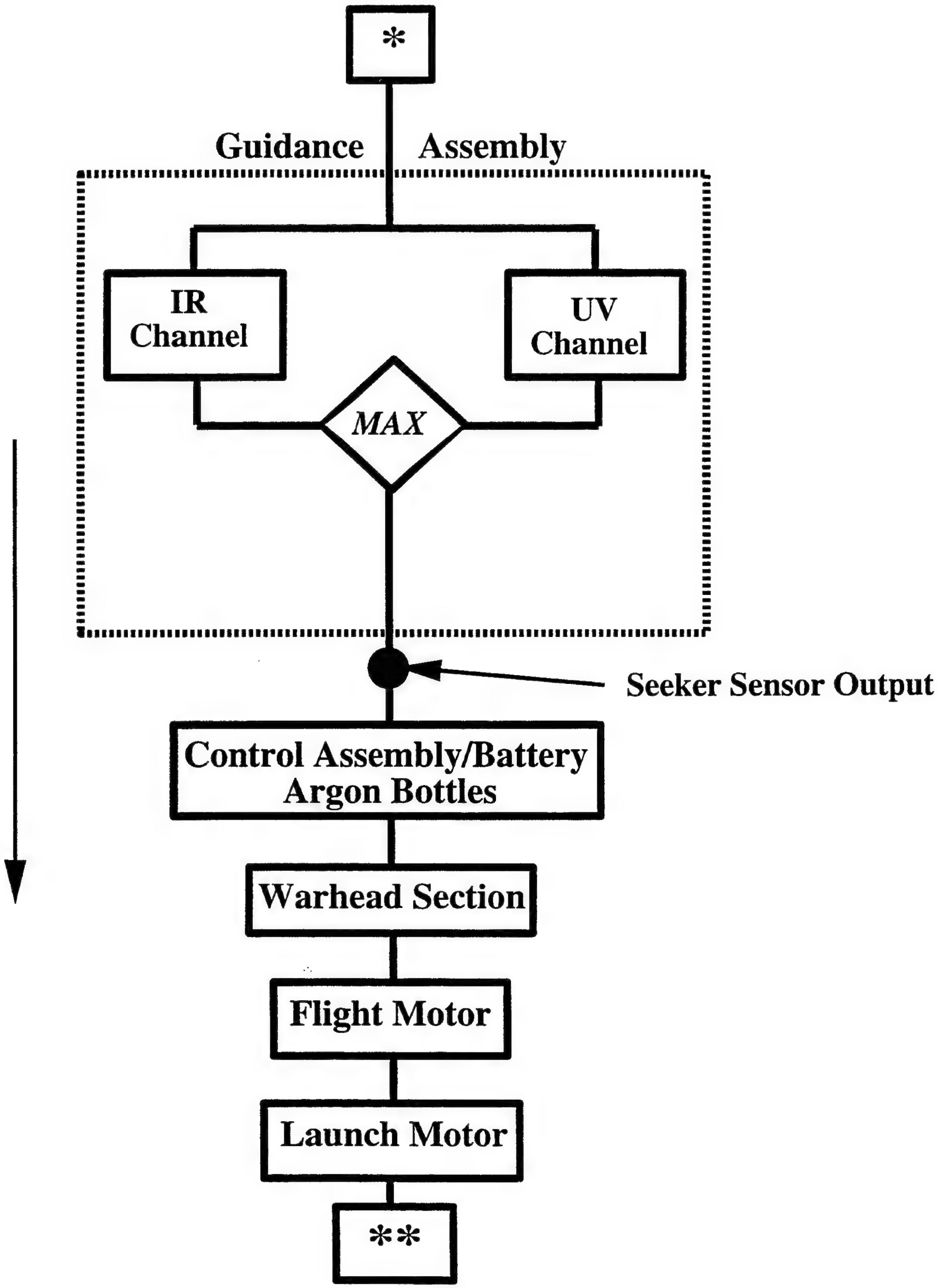

Figure 14. Embedded "Child" Tree - Stinger Missile System.

The following explanation is provided on the "crew" portion embedded within the parent fault trees for all of the Bradley Linebacker capabilities analyzed within this report. The methodology employed within this portion of the tree uses a mixture of CD and RFI states in order to calculate the soldier performance resource (where the resource is a time-dependent set of actions required for a task). For example, Figure 15 illustrates a portion of a fault tree containing the crew. After determining which skills were necessary for each capability, a priority was established among the crew members (Papke 1996). Once this was established, a correction factor (CF) was determined for each crew member. A CF is a number stating how long it takes a member of the crew to complete a task or skill while wearing MOPP IV gear. Then from this data, an overall correction factor (OCF) is achieved by the summation of the product of CFs and a weighted value (WT) (i.e., [$OCF = (CF_1*WT_1) + (CF_2*WT_2) + ... + (CF_m*WT_m)$, where m = the number of skills used in a category]) (Kelley 1995). A weighted value is a number to determine what percentage of total time a crew member spends perform that skill. This OCF was then incorporated into a degradation value (DV) for each crew member. A DV is a number that indicates the effectiveness of a crew member while wearing MOPP IV. For instance, a DV of 0.66 means the soldier is 66% effective in MOPP IV, and, since the DV is the reciprocal the OCF, which equals 1.52, the soldier's tasks should take approximately 52% longer to complete in MOPP IV as compared to MOPP 0 conditions, since

$$DV = \frac{1}{OCF} = \frac{\text{Time required to do a task in MOPP 0}}{\text{Time required to do a task in MOPP IV}}.$$

Though the crew is cross-trained, the commander is given first priority in the example, therefore evaluated first, and if he/she is somehow incapacitated, then the gunner is the crew member that has the responsibility to enable the respective capability. If the commander is alive and able to perform this task, then the next step in determining his/her task worth is by using the DV.

This final value then represents the crew member RFI state within a specific fault tree. In a scenario where the only source of component interruption is MOPP IV compatibility, the crew member RFI state is directly mapped into the residual capability state of which the crew member is a component. For a detailed explanation of DVs, see Kelley (1997).

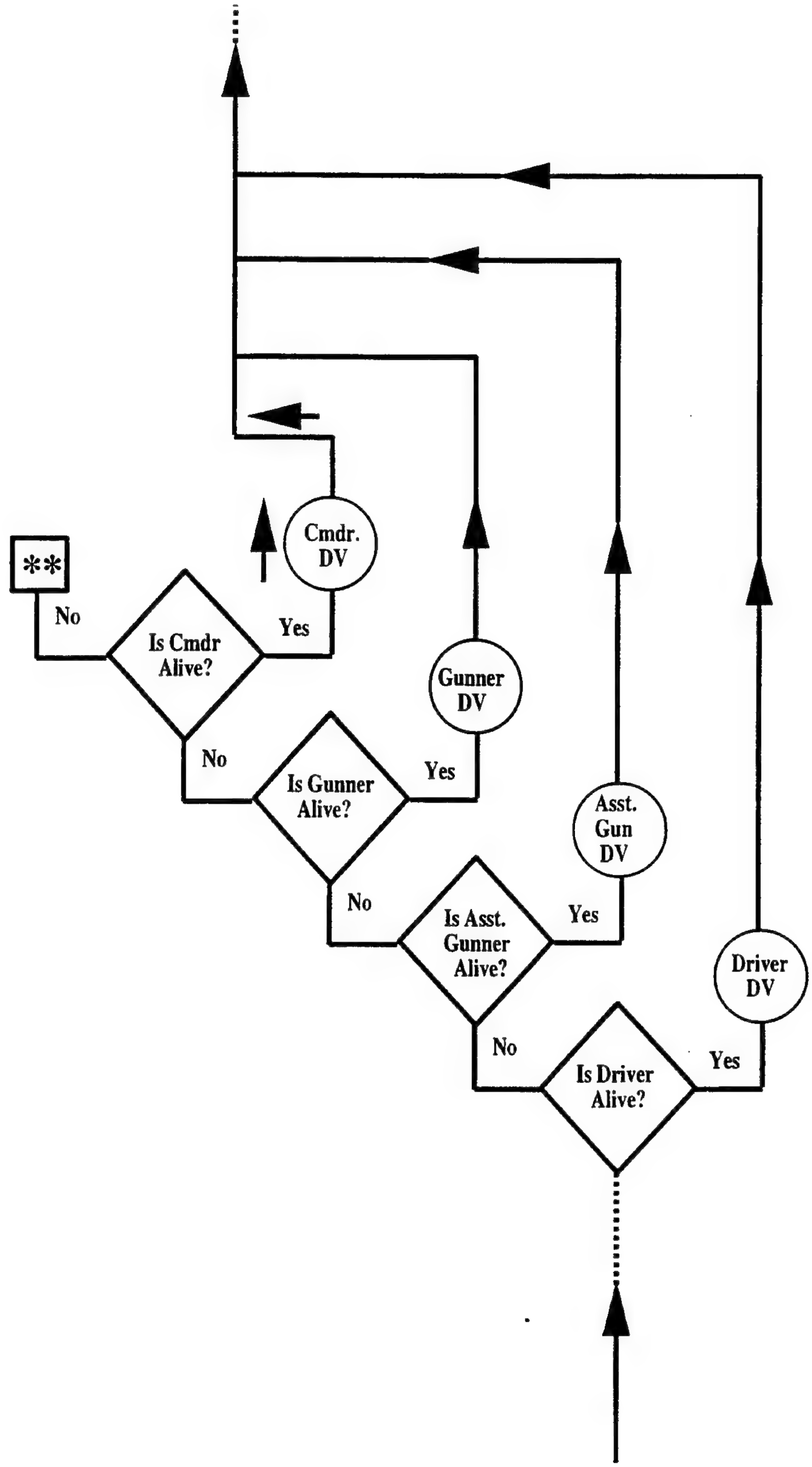

Figure 15. Portion of "Parent" Tree Containing the Crew.

3. Conclusions

This integrated fault tree methodology proved to be successful in the system analysis of the Bradley Linebacker in that it was used to assess the vulnerability throughout the whole threat spectrum. This fault tree methodology is also the first ever produced, where the effects of synergistic battlefield threats were implemented in order to produce battlefield capabilities. Since Boolean was designed for calculation with binary metrics (0 and 1), we need to specify the limitation in using Boolean logical operators to combine fractional metrics between 0 and 1 when evaluating RFI due to MOPP IV. This limitation entails the necessary assumption that the subsystem represented by a fault tree mathematically behaves as a linear system. This simply means that the aggregated net component state of a set of components logically linked together in series is equal to the product of each independent component state.

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Appendix:

Boolean Operations on Lukasiewicz Three-Valued Logic

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Since the conventional fault tree methodology used in a vulnerability/lethality (V/L) analysis utilizes Boolean operations on binary (two-valued) logic, the conventional methodology needed to be extended to accommodate the aforementioned approximate states. Thus, within the context of nonmeasurable level-2 metrics, the extended methodology was required to address three different allowed values of component functionality: 1 (fully functional), 0 (fully nonfunctional), and APPROX (for an approximate damage state reflecting some unquantifiable amount of component damage that may or may not result in loss of component function). In these instances, an undamaged component is assumed to be fully functional (a state of 1), while a damaged component can only be represented by an approximate state (a state of APPROX); in the case where a catastrophic component kill is likely due to level-1 threat initial conditions, the analyst might choose to estimate the component state as fully nonfunctional (a state of 0).

Boolean operations on 1, 0, and APPROX follow the rules of a three-valued logic as originally proposed by Lukasiewicz in 1920.* Tables A-1, A-2, and A-3 illustrate the truth tables produced by applying the logical AND, OR, and NOT (negation) operators, respectively, on this three-valued logic. As is seen from these tables, removal of the APPROX state collapses the Lukasiewicz logic to the standard binary logic.

Table A-1. Boolean Operations on the Lukasiewicz Three-Valued Logic: the AND Operation

AND	0	APPROX	1
0	0	0	0
APPROX	0	APPROX	APPROX
1	0	APPROX	1

* Borkowski, L., and J. Slupecki. "The Logical Works of Jan Lukasiewicz." *Studia Logica*, vol. 8, pp. 7–56, 1958.

Table A-2. Boolean Operations on the Lukasiewicz Three-Valued Logic: the OR Operation

OR	0	APPROX	1
0	0	APPROX	1
APPROX	APPROX	APPROX	1
1	1	1	1

Table A-3. Boolean Operations on the Lukasiewicz Three-Valued Logic: the NOT Operation

	NOT
0	1
APPROX	APPROX
1	0

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This report presents a version of the degraded states (DS) methodology, concentrating on the logic used within fault trees. This methodology was the basis for the system analysis conducted on the Bradley Linebacker. This methodology and analysis were documented within the System Analysis Report (SAR) of J. F. Meyers, B. G. Ruth, and R. W. Kunkel entitled, "Survivability/Lethality Analysis Report for the Bradley Linebacker," from the U.S. Army Research Laboratory, Aberdeen Proving Ground, MD in October 1996, in support of the U.S. Army Operational Evaluation Command (OEC) in the preparation of the System Evaluation Report (SER). The Bradley Linebacker is an enhancement to the Bradley Fighting Vehicle (M2A2) with the ability to select targets, automatically track targets, and launch Stinger missiles. This is the first integrated system performed on any system where synergy of different battlefield threats was considered.

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